Plasma Jet Takes Off

Plasma, a type of ionized gas, is usually associated with extremely high-temperature regions (such as the sun's corona) or low-temperature, low-pressure regions (such as the tail of a comet). Now, thanks to a series of joint research projects at Los Alamos National Laboratory, Beta Squared (a subsidiary of Photronics) in Allen, Texas, and the University of California at Los Angeles, this celestial substance may be brought to bear on such earthly problems as the cleaning of semiconductor chips and the cleanup of chemical, bacterial, and even nuclear contaminants.

According to John Festa, vice president of the plasma division at Beta Squared, the semiconductor industry uses tremendous amounts of water and highly corrosive, environmentally toxic chemicals in the semiconductor manufacturing process. Says Festa, "With microprocessors getting smaller and smaller, the size of the 'killer particle' [that will] cause failure is getting correspondingly smaller as well, so a clean product is vital." A new process using plasma technology enables manufacturers to make cleaner semiconductor chips and do so in a cleaner, more sustainable way.

The traditional manufacturing process involves running the semiconductor through a series of acid baths and deionized water baths to remove contaminant particles and photoresist residue. Festa says the average semiconductor manufacturing process uses about 130,000 gallons of water daily, a figure that is predicted to increase to 500,000 gallons as the industry moves from a 200-mm semiconductor to a 300-mm component. The process also uses about 20,000 L of a 95% sulfuric acid solution and 5,000 L of a 49% hydrofluoric acid solution. So, says Festa, "You have a high-water-use problem, which is a real concern in water-conscious states like Arizona and California; you have the use of some really nasty acids; and you have the problem of dealing with . . . the particles or chemicals removed in the manufacturing process. I think [the] team at Los Alamos has hit on the solution."

A Commercial Jet

A team led by Gary Selwyn, a principal investigator in plasma physics at Los Alamos National Laboratory, has developed the Atmospheric Pressure Plasma Jet (APPJ) as a solution to the problem of microprocessor contamination and waste production. In this device, selected gases such as helium (which allows ionization at low temperatures and thus helps to prevent arcing and the creation of thermal, or high-temperature, plasmas) act as nonreactive "carriers" for small amounts of the more chemically reactive oxygen. The gas mixture is pumped into a tube housing two concentric cylindrical electrodes that create a 500–900 volt per centimeter field. As the gas is forced between the electrodes, this field strips electrons off the oxygen molecules, creating ionized gas, or plasma. The ions and electrons produced through this process are used to boost the energy of other gas molecules in the tube, thereby creating what are known as metastable molecules, such as oxygen and sulfur. Metastable molecules have an anomalously long lifetime, says Selwyn, and "that's what we want, because they can go further out of the plasma being generated before they begin to break down." The process also creates oxygen and hydroxyl radicals. These radicals are ejected from the tube onto the surface to be cleaned, where they react with the target molecules in a process similar to oxidation and remove them from the semiconductor surface. Says Selwyn, "In current technology, which is a solvent-based cleaning, you have the production, transportation, storage, and disposal of chemicals to deal with. We can use this jet to oxidize contaminants, producing nothing more dangerous than carbon dioxide and water."

The APPJ functions at relatively low temperatures (approximately 175°C), which allows it to clean without damaging the microprocessor. Because the by-product metastable oxygen lasts less than one-tenth of a second before returning to ordinary oxygen, the APPJ can be considered an environmentally benign process. It also produces atomic oxygen as an oxidizing agent. According to Selwyn, the process does produce a small amount of ozone (5–100 parts per million) as a by-product, a figure the Los Alamos team is working to reduce.

The first commercial test of the device took place in 1998, when the nylon products division of DuPont contracted with Los Alamos to clean the small metal drums the company uses to manufacture approximately 3 billion pounds of nylon each year. According to Rita Heckrotte, a research associate at the DuPont Nylon Fiber Engineering Technology Center, the manufacturing process coats the drums with a harmless but messy residue that can interfere with operability. The residue is traditionally cleaned up by removing the drums and subjecting them to extended heating, followed by rinsing in a water-based cleaning solution. "Normally," says Selwyn, "DuPont would have to take the drums out of the machinery and send them to be cleaned off site. Using the plasma jet, we were able to clean the drums on site in less than 10 minutes, with no waste products generated except some completely benign gaseous by-products." Heckrotte says that while the company is still evaluating the economic feasibility of the process, results to date are very promising. "Nylon is in an incredible cost crunch so we have to plan our projects carefully," she says. "While we haven't yet had many drums to clean, the tests we've run to date have been very successful. The technology worked exactly as promised, and if we can install this process in-line, it may well save us significant production time."

A Military Jet

The APPJ has attracted the attention of the U.S. military. According to Donald A. Henderson of the Johns Hopkins Center for Civilian Biodefense Studies in an article in the 26 February 1999 issue of *Science*, the United States is woefully unprepared to deal with one of the greatest threats in the world today—a terrorist assault on public health through the release of either bacteriological or chemical warfare agents. "Of the weapons of mass destruction (nuclear, chemical, and biological)," Henderson wrote, "the biological ones are the most greatly feared, but the country is least well equipped to deal with them."

According to Selwyn, the typical decontamination process for a chemical or biological exposure involves large amounts of highly corrosive substances, such as concentrated bleach or DS2 (a decontaminant used by the military). These corrosives—which act on metals, plastics, rubber, paint, leather, and human skin—cause the same manufacturing, storage, transportation, and disposal problems as the cleaning compounds used by the semiconductor industry. They also take some time to work (up to 30 minutes) and require thorough wetting of the contaminated object, making them unusable for such items as computers and other complicated electronic circuitry.

The APPJ has been tested against *Bacillus globigii* as a surrogate for *Bacillus anthracis* (the organism that causes anthrax), resulting in the destruction of 10 million bacterial spores in 30 seconds. "Anthrax is a terrorist weapon of choice," Selwyn says. "It's cheap, and a few pounds of it, properly distributed, could take out an entire city. You could use DS2 to detox an area, but then you'd have to tear it down, and you certainly couldn't use it on the interior of vehicles or on sensitive electronics."

The APPJ was also tested on 2-chloroethyl phenyl sulfide, a simulant (or safer but compositionally similar chemical) of mustard gas. It was found to be equally effective, leaving only an oxidized simulant, which indicates a reduction of the original compound by greater than five orders of magnitude. Selwyn says the plasma jet is also being tested on VX nerve gas in cooperation with the U.S. Army. "VX is more toxic and more persistent that Sarin," he says. "VX can linger for months while Sarin dissipates in as little as five days, and VX is already in the stockpiles or within the capabilities of many rogue nations."

According to Selwyn, the APPJ may also be used one day to clean up radioactive waste spills. To destroy radioactive waste, the APPJ uses a feed gas containing fluorine to generate atomic fluorine, which reacts with actinides to form substances such as uranium hexafluoride, a substance that is more easily disposed of.

Using the APPJ on radioactive substances produces volatile gases that must be contained. "So we capture the volatile radioactives in a filter," says Selwyn. "You can do this process with nitric acid; by pouring it onto the contaminated material, you dissolve the actinide, but then you're left with a mixed waste—radioactive acid—which is very dangerous. Not only that, but the generation of such wastes is illegal, leaving only burial as a way to handle contaminated objects. Using the APPJ reduces the contaminant to a much smaller, easier-to-handle form and volume."

Jet Stream

Selwyn has some big plans for the APPJ—or small plans, depending on how you look at it. One plan is to scale up the unit, creating a hangar-sized "plasma car wash" that could decontaminate a military or civilian vehicle, even something as large as an airplane. Says Selwyn, "We're looking at other gas combinations that can reduce costs or enhance performance, and we'd like to minimize the need for the helium carrier gas to reduce the need to transport cylinders of gas." Another plan is to make the unit smaller, so that one person can transport and operate the unit. Selwyn also envisions a battery-powered unit for use by military personnel for decontaminating biological weapons storage bunkers.

Larger-scale and portable applications are still some ways off, as is one of the most fascinating potential applications for the APPJ—the decontamination of humans exposed to chemical agents. Key to this effort is Selwyn's work in lowering the temperature at which the plasma jet can function effectively. "Obviously, 270°C is too high, but we've managed to lower the temperature to as low as 70°C [158°F]," he says. "That's a bit of a slow cook; it's probably better than a Clorox shower, which is the current method, but it wouldn't be comfortable. The goal we've been set by [the Department of Defense] is 60°C or below." Selwyn says the Department of Defense is picturing a plasma "shower" that people could walk through. He says, "Of course, they'd need eye protection and breathing apparatus, but it's not out of reach. The problem with lower temperatures is that it takes longer to kill something like anthrax, but as we continue to learn more about the physics of the plasma discharge and also how the spores are killed, we get closer."

Selwyn says it's important to keep in mind that the plasma jet technology is only three and a half years old. "For certain applications, we're quite close," he says, "but for others, it's still down the road. This is a new technology with tremendous promise, and the more we learn, the more promise opens up."

Lance Frazer

Suggested Reading

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